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Field and laboratory evaluation of soil quality changes resulting from injection of liquid sewage sludge

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Abstract

Soil quality changes resulting from repeated or single injection of liquid municipal sewage sludge were evaluated in terraced cropland in eastern Nebraska, USA. Differences in soil properties among sampling locations were explained primarily by two factors, landscape position and sludge injection. Selected chemical properties (pH, EC, NO_3–N) did not generally differ between landscape positions, but soil organic matter (organic C and N) and microbial activity indices (soil respiration, biomass N, available N, mineralization and nitrification rates) were more sensitive indicators of change. Values of these indicators generally increased down-slope from the upper terrace to the grassed waterway on a west facing slope. A probable similar pattern on the east slope was obscured by repeated application of sludge. Single or repeated (long-term) sludge injection increased the readily decomposable organic matter, ammonium- and available-N in soil (0–30.5 cm depth). These changes stimulated soil microbial activity as evidenced by increased basal respiration, net mineralization and nitrification rates. Consequently, nitrification of ammonium-N was reflected in soil chemical properties as increased soil nitrate-N (to levels that were more than two times higher than sufficiency levels for corn) and EC and by decreased pH. In-field measurements detected changes in physical properties such as a decrease of infiltration rate caused by sludge injection and soil compaction as a result of traffic operations. Differences between the sites of single and repeated sludge injection were found in soil pH, ammonium-N, organic matter and microbial activity. Recent sludge injection resulted in higher ammonium-N concentration and higher microbial activity in soil, and repeated sludge injection resulted in lower pH and in greater organic matter content. Regardless of these differences in soil properties between the sites of single and repeated sludge application, the overall changes that were caused by sludge injection had both positive and negative effects on soil quality and the sustainability of this management practice. Increase of organic matter content and biological activity improved soil fertility, but excessive amounts of ammonium salts contained in liquid sludge resulted in soil nitrification, excessive nitrate formation and acidification. These processes reduce soil productivity, increase the risk of ground- and surface-water contamination and pose a threat to plant and animal health. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The application of domestic sewage sludge to agricultural land has become an acceptable method of waste disposal and soil amendment. A great number of studies have been published which document the effects of sludge application on soil properties, nutrient availability and crop growth, heavy metal toxicity, degradation of organic pollutants, and contamination of surface and ground water. Studies of soil property changes have selectively focused on nutrient enrichment and deficiency, organic matter dynamics, chemical toxicities, microbial and enzymatic activity and soil physical parameters (Metzger and Yaron, 1987; Smith, 1991; Berti and Jacobs, 1996; Smith, 1996; McBride et al., 1997). Sewage sludge application to soil generally improves soil fertility by increasing the soil organic matter, microbial activity and residual nitrogen and by improving soil physical properties. Reduced bulk density and increased porosity, improved aggregate stability and enrichment of soil organic carbon result generally in increased water retention capacity and available water in coarse-textured soils and, in the long-term, in enhanced water transmission properties as defined by improved hydraulic conductivity and increased infiltration. However, it is necessary to apply sludge at large rates, exceeding the maximum recommended level of N application in manures, or at repeated low levels in order to gain a significant improvement of soil physical properties (Hall and Coker, 1983; Metzger and Yaron, 1987; Smith, 1996). It is these high rates of application that exceed crop N requirements which may cause undesirable changes in soil chemical properties such as excessive soil acidification from nitrification of the added ammonia, accumulation of nitrates in sludge-treated profiles and increased nitrate leaching from susceptible loamy soils (Bergstrom and Brink, 1986; Speirs and Frost, 1987; Chang et al., 1988; Jansson et al., 1989; Powlesland and Frost, 1990).

Recent efforts for integrated soil quality assessment recognize the need for reliable indicators of soil productivity, environmental quality and plant/animal health. In this study, a combination of physical, chemical and biological soil properties were used for the evaluation of soil quality changes as a result of single and repeated injection of liquid digested sludge in an agricultural soil. The selected measurements comply with the proposed selection criteria of soil quality indicators in that they are sensitive to variations in management, they define major ecological processes in soil and they reflect conditions as they actually exist in the field under a given management system (Doran et al., 1996). Soil injection of sludge is widely practiced and significantly reduces ammonia loss by volatilization, but leads to increased leaching of N as compared to surface application (Williams and Hall, 1986; Smith, 1996). In this case, sludge was injected to shallow depth for close proximity to crop roots in the fall in order to minimize leaching losses (Shepherd, 1992; Smith, 1996). The specific objectives of this study were the assessment of soil quality changes caused by (a) repeated (long-term) liquid sludge injection at cumulative loadings that correspond to the maximum annual recommended level of N application in organic manures, (b) single sludge injection at rates exceeding the maximum annual recommended level of N application and (c) landscape position as compared to sludge injection effects.

2. Methods

2.1. *Site description and sludge application*

The experimental site is located in Lancaster county NE, north of the city of Lincoln, NE, and is a terraced dryland of east and west facing slopes meeting in a grass waterway. Each slope was composed of an upper and a lower terrace which, together with the waterway, resulted in five different sampling locations. The soil type was Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudoll).

The upper East terrace received anaerobically-digested liquid sewage sludge from the NE Lincoln sewage treatment plant by injection every three years since 1982 at an estimated cumulative loading of 52 Mg ha^{-1} of dry solids (ds) over a 12-year-period for an average of 10.4 Mg ds ha^{-1} (674 kg N ha^{-1}) per injection which corresponds to 3.5 Mg ds ha^{-1} year^{-1} (225 kg N ha^{-1} year^{-1}). In terms of N, this is close to the maximum annual rate that is recommended for the application of organic manures (CEC, 1991; MAFF, 1991) in order to control nitrate contamination of groundwater in potentially susceptible areas. The site was cultivated to wheat without inorganic fertilizers in order to reduce excessive soil nutrient loadings, the herbicide Roundup was used to kill the wheat and the soil was disc-tilled prior to sludge application. In addition, a 3.9-acre section of the lower East terrace was reported to have received 458,514 L of sewage sludge (2.9% dry matter content, 8.4 Mg ds ha^{-1} or 608 kg N ha^{-1}) for the first time on 30 August, 1995. In terms of N, this rate is three times higher than the recommended maximum annual application rate of organic manures (CEC, 1991; MAFF, 1991), but in terms of organic solids it is three times lower than the suggested rates for a significant improvement of soil quality with respect to soil physical properties and organic matter content in sandy loam soils (Smith, 1996). The sludge was applied by injection to a depth of 20 cm below the soil surface in rows of ca. 64 cm apart by a caterpillar track vehicle. The chemical characteristics of the applied sludge are presented in Table 1.

Table 1
Chemical composition of liquid sewage sludge (pH 7) injected in 1.6 ha of the lower east terrace on 30 August, 1995

Component	Reported concentration	
	mg kg^{-1}	dry kg ha^{-1}[a]
Total solids	28900	8398
Volatile solids	15850	4606
Total Nitrogen	72457	608
Organic N	45730	384
Ammonium N	26740	224
Nitrate N	6.8	0.06
Phosphorus	10435	88
Sulfate	6207	52
Iron	11768	99
Potassium	6290	53
Heavy metals and other		
Arsenic	9.6	0.08
Cadmium	5.9	0.05
Chromium	43.4	0.36
Copper	1163	9.8
Lead	222	1.9
Manganese	487	4.1
Mercury	4.6	0.04
Molybdenum	59.8	0.50
Nickel	65.5	0.55
Selenium	1.5	0.01
Silver	59.2	0.50
Zinc	2292	19.25

[a] Assuming 2.9% dry matter content and 290 538 L ha^{-1} as the reported sludge application rate.

2.2. Soil sampling and analysis

An overview of the sampling scheme is given in Table 2. Five random composite samples (0–30.5 cm depth) were taken with a step-down Oakfield probe from each landscape position on 29 August and from sludge application (row) and non-application (inter-row) zones of the lower east terrace on 14 September, 1995. After mixing in a bucket, the samples were sealed in plastic bags, placed in a portable cooler and taken to the laboratory. Samples were sieved through a 2 mm sieve at field moisture content prior to analysis. Standard laboratory analysis of physical and chemical properties of composite soil samples included gravimetric water content, bulk density (BD), nitrate and ammonium nitrogen by extraction with 2 M KCl and colorimetric determination with a flow injection analyzer (Keeney and Nelson, 1982) followed by adjustment for 1 : 1 soil-water mixture from air-dried soil, pH and electrical conductivity (EC) adjusted for 1 : 1 soil-water mixture, total C and N by dry combustion of samples in an elemental analyzer (Schepers et al., 1989), potentially mineralizable N (available N) by the quantity of ammonium-N produced during incubation of soil samples for 1 week at 40°C under waterlogged conditions (Keeney, 1982). Measured soil biological properties included basal soil respiration by gas chromatographic analysis of headspace CO_2 after aerobic incubation of samples in sealed 1.9 L jars, net mineralization/ nitrification rates after analysis of the incubated samples for ammonium- and nitrate-N, biomass C by gas chromatographic analysis of headspace CO_2 of untreated and fumigated samples with chloroform and biomass N by determination of mineral nitrogen of the same samples. For the estimation of basal soil respiration, soil biomass, net mineralization and nitrification, non-fumigated soil samples were incubated at 55% water-filled pore space and 25°C for 20 days. Biomass C and N was determined by the fumigation/incubation method of Jenkinson as described by Rice et al. (1996).

Replicated surface soil samples (0–7.6 cm depth) were also taken from the lower east terrace on 14–15

Table 2
The soil sampling scheme (site, sampling depth, date) of the experimental area in order to test the effects of landscape position and sludge injection

Site	Sludge injection	Sampling depth (cm) and site selection to test effect of		
		Landscape position	Repeated injection	Single injection
		29 August		14 September
Grass waterway	No	30.5		
West upper terrace	No	30.5	30.5	
West lower terrace	No	30.5	30.5	
East upper terrace	Repeated		30.5	
East lower terrace	No	30.5	30.5	7.6
	No (inter-row)			7.6/30.5
	Single (row)			7.6/30.5

September, 1995, 2 weeks after sludge injection. Soil samples were collected with aluminium sampling tubes (7.4 cm inside diam.) from three consecutive rows and inter-rows in a perpendicular line so that the distance between two consecutive samples was 32 cm. Three additional top soil samples were taken from the adjacent part of the terrace which had not been subjected to sludge injection (control samples). These samples were analyzed for gravimetric water content, bulk density, electrical conductivity, nitrate-N and pH in the laboratory as described above. On-site water infiltration rate was measured within aluminum infiltration rings (15 cm inside diameter) which were inserted to a 7.6 cm soil depth. Soil respiration (pre- and post-irrigation) was measured from the headspace of infiltration rings covered for 30 min using Draeger tubes. Post-irrigation top soil samples from within the irrigation rings were taken with the sampling tubes and analyzed for soil bulk density and water holding capacity (WHC). Further details of the field soil quality procedures used are given by Sarrantonio et al. (1996).

2.3. *Statistical analysis*

Analysis of variance (ANOVA) was performed on data obtained from replicated surface soil samples. Sludge treatment was the independent factor of the model in a completely randomized design. Neuman–Keuls post hoc comparison of means was used at the level of $p < 0.05$. Correlation coefficients were computed between all microbial indices measured for 0–30.5 cm depth by standard analytical procedures. All the employed procedures are reported in StatSoft (1995).

3. Results and discussion

Bulk density, electrical conductivity, pH, nitrate and ammonium N of the initial deeper soil samples (0–30 cm) were similar in all terraces except those of the upper east terrace which had repeatedly received sludge since 1982. The upper east terrace had higher soil conductivity, nitrate and ammonium levels and lower pH than the other terraces (Table 3). Electrical conductivity was positively related to nitrate concentration in all landscape positions except the waterway (Table 3). Elemental analysis and anaerobic N mineralization showed a progressive increase of total C and N and available N down the slope of the west side to the waterway (Table 3). With the exception of biological indices involving microbial C, all other indices of microbial activity followed a similar increasing trend with lowest values in the upper west terrace. Basal soil respiration, biomass N and its proportion to total N ($N_b : N_t$) had the highest values in the grassed waterway, the last two indices having values at least two times higher than those of the west terraces. This progressive increase in soil fertility was probably caused by lateral leaching and surface erosion from higher elevations. A possible similar pattern on the east slope was obscured, and reversed, by sludge application in the upper east terrace. Total C and N, N availability and all biological indices had higher values in the upper than the lower east terrace due to

Table 3
Soil quality changes as a result of landscape position and repeated sludge application

Soil quality indicator	Water-way (grass)	Terrace position			
		Lower west	Upper west	Lower east	Upper east[a]
Physical					
Soil bulk density (g/cm^3)	1.38	1.43	1.49	1.42	1.41
Chemical					
Soil $EC_{1:1}$ (dS/m)	0.30	0.12	0.16	0.12	0.30
Soil pH	6.79	6.46	6.35	6.24	5.96
Soil NO_3–N (kg NO_3–N/ha 30.5 cm)	7.1	25.0	18.9	20.2	156.7
Soil NH_4–N (kg NH_4–N/ha 30.5 cm)	4.2	4.7	1.0	4.4	20.5
Total C (kg C/ha 30.5 cm)	58467	37920	19529	31163	34811
Total N (kg N/ha 30.5 cm)	5817	4838	3234	4017	5011
C/N Ratio	10.1	7.8	6.0	7.8	6.9
Biological					
Biomass C (kg C/ha 30.5 cm)	396	1299	794	218	1476
Biomass N (kg N/ha 30.5 cm)	126.7	45.6	43.7	30.6	66.9[e]
Biomass C : N	3.1	28.5	18.2	7.1	-
Available N (kg NH_4-N/ha 30.5 cm)[b]	113.2	60.0	38.4	36.4	75.3
Available N: Total C (mg/g)	1.9	1.6	2.0	1.2	2.2
Available N: Total N (mg/g)	19.5	12.4	11.9	9.1	15.0
Net mineralization (kg/ha 30.5 cm/day)					
0–10 days	2.32	2.27	0.06	0.75	−2.30
0–20 days	1.54	1.59	0.33	0.43	1.87
Net nitrification (kg/ha 30.5 cm/day)					
0–10 days	2.64	2.67	0.09	1.12	−0.30
0–20 days	1.73	1.82	0.37	0.64	2.86
Respiration (kg CO_2–C/ha 30.5 cm/day)[c]					
0–10 days	4.76	2.71	3.19	1.76	2.81
10–20 days	3.18	1.37	1.94	1.08	1.32
0–20 days	3.97	2.04	2.57	1.42	2.07
Biomass C: total C, %	0.7	3.4	4.1	0.7	4.2
Biomass N: total N, %	2.2	0.9	0.8	1.4	
Specific respiratory activity[d]	10.0	1.6	3.2	6.5	1.4

[a] Injected with sewage sludge every 3 years since 1982.
[b] NH_4–N released during anaerobic incubation for 1 week at 40°C.
[c] 2.25 cm depth.
[d] qCO_2 (mg CO_2-C g^{-1} biomass C day^{-1}).
[e] Error due to presence of readily decomposable organic material resulting from sludge injection.
Values represent single measurements of composite samples (0.30.5 cm depth, $n = 5$) taken on 29 August, 1995.

long-term sludge application (Table 3). The higher ratio of available N: total C in the soil of repeated sludge injection is indicative of the presence of readily decomposable organic material.

The effects of the single sludge injection at the lower east terrace were similar to those of repeated sludge injection. The treated soil (sludge rows) had greater organic matter content, microbial activity,

Table 4
Effects of recent sludge injection on indicators of soil quality

Soil quality indicator	Area of sludge injection		Ratio Sludge/no-sludge
	Application row (sludge)	Inter-row (no-sludge)	
Physical			
Soil bulk density (g/cm^3)	1.36	1.35	1.0
Chemical			
$EC_{1:1}$ (dS/m)	0.37	0.10	3.7
Soil pH	6.28	6.71	0.9
Soil NO_3–N (kg NO_3–N/ha 30.5 cm)	172.2	8.9	19.4
Soil NH_4–N (kg NH_4–N/ha 30.5 cm)	67.2	3.0	22.4
Total C (kg C/ha 30.5 cm)	20312	17282	1.2
Total N (kg N/ha 30.5 cm)	3826	2724	1.4
Biological			
Biomass C (kg C/ha 30.5 cm)	−205[b]	138	
Biomass N (kg N/ha 30.5 cm)	−69.0[b]	22.7	
Available N (kg NH_4–N/ha 30.5 cm)[a]	66.5	18.0	3.7
Available N: total C (mg/g)	3.3	1.0	3.3
Available N: total N (mg/g)	17	7	2.4
Net mineralization (kg N/ha 30.5 cm/day)			
0–10 days	8.18	0.29	28.2
0–20 days	8.00	0.32	25.0
Net nitrification (kg NO_3–N/ha 30.5 cm/day)			
0–10 days	14.57	0.50	29.1
0–20 days	11.26	0.46	24.5
Respiration (kg CO_2-C/ha 30.5 cm/day)			
0–10 days	34.8	16.8	2.1
10–20 days	36.9	12.3	3.0
0–20 days	35.9	14.6	2.5

[a] NH_4–N released during anaerobic incubation for 1 week at 40°C.
[b] Error due to presence of readily decomposable organic material resulting from sludge injection.
Values represent single measurements of composite samples (0–30.5 cm depth, $n = 5$) taken on 14 September, 2 weeks after sludge application.

available N, mineral N and electrical conductivity and decreased pH relative to the untreated soil of the inter-rows, 2 weeks after sludge injection (Table 4). Digested sludge injection at a rate of 608 kg N ha^{-1} was three times higher than the recommended maximum application of organic manures (160 or 210 kg N ha^{-1} year^{-1}; CEC, 1991), four times higher than the range of 100–160 kg N/ha estimated to be the 'breakpoint' which prevents nitrate leaching for cereals (Bergstrom and Brink, 1986; Jansson et al., 1989) and, based on calculations of Powlesland and Frost (1990), may be expected to increase groundwater concentration by approx. 9 ppm NO_3-N. Two weeks after injection, the majority (72%) of the ammonium-N contained in sludge was converted to soil nitrate-N whose concentration raised to levels that were two times higher than sufficiency levels for corn during early growing season (20–25 ppm, Bundy and Meisinger, 1994, p. 958), which equated to 80–100 kg ha^{-1} in the top 30 cm. Sufficiency levels for manured soil are even lower at about 16 ppm or less that equate to <66 kg ha^{-1} (Practical farmer, 1997).

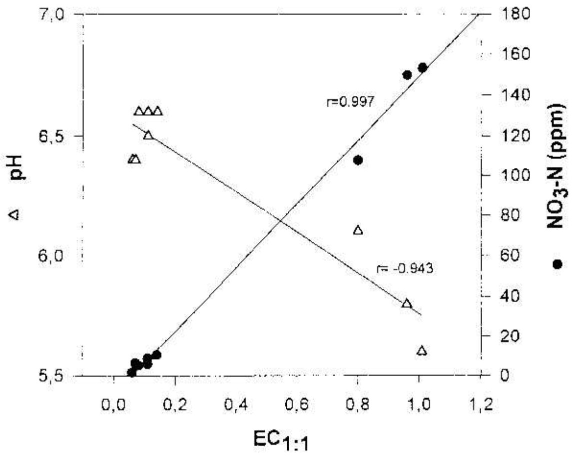

Fig. 1. The linear relationship between electrical conductivity (EC), nitrate-N and pH in surface soil samples of sludge-treated and untreated sites taken on 14 September, 1995.

Such high soil nitrate levels in the site of recent sludge injection, but also in the site of long-term sludge injection even after several years of wheat cultivation (Table 3), pose a serious risk for groundwater contamination and animal health through excessive accumulation of N in plant tissues. Accumulation of nitrate in sludge-treated soils has also been reported by others (Speirs and Frost, 1987; Chang et al., 1988) and resulted from nitrification of ammonium contained in the anaerobically-digested sludge (Table 1) which caused a rise in EC and a decline of pH as evidenced by the significant correlation of these three variables in the replicated surface samples (Fig. 1, Table 5). The relationship between nitrate-N and EC is also reported in a given system or region for agricultural soils cultivated with various crops and treated with organic or synthetic fertilizers (Patriquin et al., 1993). Excessive soil acidification is known to occur from nitrification of ammonium contained in sludge and inorganic fertilizers and can lead to reduction of crop yields (Speirs and Frost, 1987; Smith and Doran, 1996). A single sludge injection lowered the pH of deeper soil cores by 0.4 units in the sludge application row (Table 4) and repeated sludge injection further reduced soil buffering capacity as evidenced by pH values below six (Table 3). Although this acidification process does not affect the current cropping management, which is characterized by the growth of pH-insensitive crops such as grain, future rotations with alfalfa or clover will result in significantly reduced yields.

The freshly incorporated and readily decomposable organic matter, in the soil of single sludge injection, increased the microbial activity (mineralization, nitrification and respiration rates) to levels even higher than those caused by repeated injection. Mineralization and nitrification rates were very sensitive biological indicators of change as they were 25 times higher in the sludge rows after 20-days of incubation in the laboratory (Table 4). Soil respiration in the field (pre- and post-irrigation) of sludge rows was four times higher than that of the control soil (Table 5), although differences between sludge rows and no sludge inter-rows were not detected, possibly because of lateral gas diffusion between these adjacent sites. Soil respiration, when adjusted for the same units and soil depth, was higher in the field than in the laboratory incubation as has been also observed by Liebig et al. (1996) when comparing top soil samples for the same depths. In our data, the greater evolution of carbon dioxide in the field was caused likely by differences in the origin of samples, i.e., different depth of sampling, and by differences in assessment methodology.

In evaluating microbial indicators of soil quality, it was noted that differences in microbial biomass between different locations were much greater than those expected to result in about 35% variation due to landscape position (Rice et al., 1996). Most determinations of biomass C and N also resulted in unusually high C : N ratios for agricultural soils (Table 3), normal values ranging between 4.5 and 6.5 (Rice et al., 1996). These observations suggest that biomass C determinations, by chloroform fumigation-incubation, were subjected to analytical errors as only biomass N (N_b and $N_b : N_t$) and available N (N_{av} and $N_{av} : N_t$) were significantly correlated to basal soil respiration ($p < 0.05$). These variables and soil respiration were also the best predictors of microbial activity, i.e., the ones having the highest degree of association with other indices of microbial activity, once biomass C data was removed from the correlation analysis. Franzluebbers et al. (1995) found soil respiration, but also microbial N and C, to have the greatest degree of association with all other microbial determinations in assessment of soil quality and fertility. Estimated values of $N_b : N_t$ ratio ranged between 0.8 and 2.2% (Table 3), falling within the commonly observed

Table 5
Surface soil properties (0–7.6 cm depth) of sludge-treated and untreated sites on September 14, 1995

Soil quality indicator	Treatment		
	Sludge		No sludge
	Application row	Inter-row	Control
Pre-irrigation			
Soil water content (g/g)	0.23	0.18	0.21
Soil bulk density (g/cm^3)	1.31	1.25	1.07
Water-filled pore space (%)	60^{a}	43^{a,b}	36^{b}
Soil $EC_{1:1}$ (dS/m)	0.92^{a}	0.10^{b}	0.09^{b}
Soil pH	5.82^{a}	6.47^{b}	6.52^{b}
Soil NO_3–N (kg NO_3–N/ha 7.6 cm)	134.8^{a}	5.8^{b}	5.4^{b}
Soil NH_4–N (kg NH_4–N/ha 7.6 cm)	32.5^{a}	0.4^{b}	0.1^{b}
Soil respiration (kg CO_2–C/ha/d) 60% water-filled pore space, 25°C	63.4^{a}	51.2^{a,b}	14.4^{b}
Infiltration time			
First inch (min)	1.7^{a}	0.4^{b}	0.7^{b}
Second inch (min)	13.2^{a}	6.0^{b}	3.2^{b}
Post-irrigation			
Soil water content (g/g)	0.28	0.26	0.26
Water holding capacity (cm^3/cm^3)	0.35	0.35	0.31
Soil bulk density (g/cm^3)	1.25^{a,b}	1.33^{a}	1.19^{b}
Water-filled pore space (%)	66	70	56
Soil respiration (kg CO_2–C/ha/d) 60% water-filled pore space, 25°C	87.6	76.6	23.6

Means ($n = 3$) within rows followed by different letter(s) are significantly different at $p < 0.05$.

range of values for soil of 1–5% (Rice et al., 1996). The inorganic N released during the 7-day anaerobic incubation was a better predictor of soil microbial respiration ($r = 0.86$, $n = 7$) than the 20-day aerobic incubation. The computed ratios of CO_2-C released to net N mineralized were highly variable, ranging from

Table 6
Comparison of microbial respiration and N mineralization indices across landscape positions and sludge application sites for a soil depth of 30.5 cm

Landscape		20 day CO_2–C respiration	20 day net N mineralization	7 day anaerobic mineralization^{d}	Ratios		
Position	Terrace	Kg C or N ha^{-1} day^{-1}			N_{net}/N_{anaer}	CO_2-C/N_{net}	CO_2-C/N_{anaer}
Waterway		54.0	1.54	1.13	1.4	35.1	47.8
West Slope	Upper	34.8	0.33	0.38	0.9	105.1	91.6
	Lower	27.7	1.59	0.62	2.6	17.4	44.7
East Slope	Upper^{a}	28.2	1.87	0.75	2.5	15.1	37.6
	Lower	19.3	0.43	0.36	1.2	44.9	53.6
	Lower^{b}	35.9	8.00	0.67	11.9	4.5	53.6
	Lower^{c}	14.6	0.32	0.18	1.8	45.6	81.1

[a] Long-term sludge application site sampled on 29 August.
[b] Single sludge injection site (rows) sampled on 15 September.
[c] Single sludge injection site (inter-rows) sampled on 15 September.
[d] Assuming that the N released by anaerobic incubation is equivalent to the potential N mineralized over 100 days under optimal conditions.

4.5 to 105 : 1 (Table 6), while Parkin et al. (1996) observed more common ratios of 10–20 : 1. In contrast, the ratios of CO_2-C released to anaerobically mineralized N were less variable, ranging from 45 to 92 (Table 6).

Infiltration rate was significantly reduced in the sludge rows (Table 5). Slurry or liquid sludge application has been reported to initially seal the soil and reduce infiltration, although time or tillage would restore the infiltration capacity (Kelling et al., 1977; USDA, 1979). None of these infiltration rates would be a cause for concern in this climatic zone. However, the relatively rapid rates of infiltration could represent a potential for leaching losses to groundwater. Effects of sludge application on field water-holding capacity were insignificant (Table 5) and expected to be minimal in fine-textured soils (Khaleel et al., 1981). The higher bulk density of the sludge row and inter-row areas is attributed to soil compaction as a result of increased traffic of the sludge injection operation.

4. Conclusions

This study demonstrated the potential usefulness of selected physical, chemical and biological indicators for an integrated assessment of soil quality in the laboratory and in the field. Organic matter and microbial measurements revealed landscape patterns that were not readily detectable by other standard physical and chemical indicators. Chemical measurements indicated that the experimental area had adequate nitrate levels, considering the time of the year, and optimal pH values to support non-limited crop growth without the need of amendments. Almost all indicators used were sensitive in detecting soil property changes as a result of sludge injection and allowed interpretations related to the type, magnitude and consequences of altered ecosystem processes.

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